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NaviFields: Relevance fields for adaptive VR navigation

Roberto A. Montano Murillo[1], Elia Gatti[1], Miguel Oliver Segovia[2],
Marianna Obrist[1], Jose P. Molina Masso[2], Diego Martinez Plasencia[1]
[1]Department of Informatics, University of Sussex, UK{rm462,e.gatti,m.obrist,dm372} @sussex.ac.uk
[2]LoUISE lab, University of Castilla-La Mancha, Spain {miguel.oliver, josepascual.molina}@uclm.es

ABSTRACT
Virtual Reality allow users to explore virtual environments naturally, by moving their head and body. However, the size of the environments they can explore is limited by real world constraints, such as the tracking technology or the physical space available. Existing techniques removing these limitations often break the metaphor of natural navigation in VR (e.g. steering techniques), involve control commands (e.g., teleporting) or hinder precise navigation (e.g., scaling user's displacements). This paper proposes *NaviFields*, which quantify the requirements for precise navigation of each point of the environment, allowing natural navigation within relevant areas, while scaling users' displacements when travelling across non-relevant spaces. This expands the size of the navigable space, retains the natural navigation metaphor and still allows for areas with precise control of the virtual head. We present a formal description of our *NaviFields* technique, which we compared against two alternative solutions (i.e., homogeneous scaling and natural navigation). Our results demonstrate our ability to cover larger spaces, introduce minimal disruption when travelling across bigger distances and improve very significantly the precise control of the viewpoint inside relevant areas.

Author Keywords
Virtual Reality; Navigation techniques; Navigation fields.

ACM Classification Keywords
I.3.6 Methodology and Techniques: Interaction techniques.

INTRODUCTION
Physical displacement in Virtual Reality (VR), where the viewpoint is directly controlled by the user's head motion [2], stand as the most natural navigation techniques for VR and benefit both interaction and sense of presence [3]. However, limitations in tracking technologies (i.e. reduced tracking volume) or in the actual physical space available (e.g. empty space in a user's living room) practically constraint the size of the Virtual Environment (VE) that users' can navigate.

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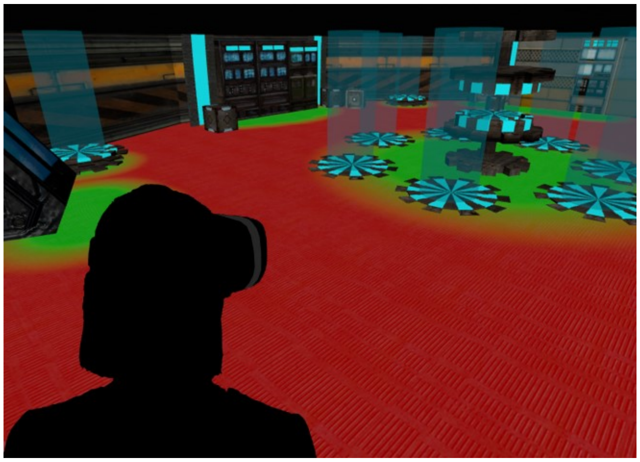

Figure 1. *NaviFields* scale user displacements dynamically, enabling natural 1:1 navigation inside areas where precise interaction is required (green) while progressively increasing their movements outside these areas (yellow, red). This allows larger navigable spaces, maintains the natural displacement metaphor and allows precise maneuvering where necessary.

Many techniques have been proposed to overcome these limitations, allowing users to navigate a virtual space bigger than the actual physical space available. Treadmills can achieve this while maintaining a natural navigation metaphor, but expenses and the need to deploy a (potentially bulky) hardware element in the users' home can limit their adoption. Teleportation or Steering (e.g. using head or hand orientation to control the direction of motion) techniques enable unconstrained navigation. However, they also break the metaphor of using physical displacements to move in VR, which can affect user's presence [3], and might only be well suited for specific scenarios (e.g. while teleportation could be adequate in a sci-fi action game in VR, it might be ill suited for simulation or training scenarios).

In this paper we propose *NaviFields*, a VR navigation technique that maintains the physical displacement metaphor [1], while expanding the size of the VE that users can navigate. With our technique users' head displacement is scaled according to their position in the VE. If the user is in an interactive area requiring fine control (e.g. assembling machinery parts), the viewpoint will follow the real motion of the head (1:1 direct navigation). In contrast, while travelling across connecting spaces (e.g. the corridor leading to the maintenance room), motion will be gradually scaled, requiring smaller displacements to cover bigger distances.

We do this by creating a *navigation field* (see Figure 1) describing the relevance (i.e. requirements for precise motion) of each point of the VE, and then use this field to determine the scaling applied to user displacements at each point. This practically compresses the overall size of the VE, but retains a direct 1:1 navigation within highly interactive areas. This is useful in, for instance, a training VE for a factory, where there is a well identified set of stations for machinery control (interactive areas requiring fine control), but at the same time the user needs to build a mental model of how these stations are arranged in the real factory.

This paper contributes a formal description of the *NaviFields* technique. We then report a quantitative testbed evaluation, assessing low-level travel tasks (search travel and maneuvering [1]), and explore the effect of using varying scaling factors, travel path lengths, maneuvering complexity and user poses. We identify the potential and limitations of *NaviFields*, by comparing its performance to the use of: **a)** physical displacements with a constant scaling factor (naïve alternative technique that maintains physical displacement and covers bigger navigable spaces); and **b)** natural navigation (baseline comparison, best case scenario).

Our results show *NaviFields* can be comparable to natural navigation in maneuvering tasks, and still allows good performance for search travel tasks. When compared to the homogeneous scaling technique, *NaviFields* showed better performance for all factors assessed (travel, maneuvering and user preference). Our results also provide useful insight about the effects of scaling or user pose in travel and maneuvering tasks; or the effects of drift in navigation techniques based on differential tracking, applicable to other non-isomorphic techniques. We finish the paper discussing the opportunities and application scenarios *NaviField* enable.

RELATED WORK

We review prior work in two related areas: (1) VR navigation techniques; and (2) Dynamic control of the viewpoint.

VR Navigation Techniques

Navigation is identified as a fundamental task for VEs, being usually decomposed [1] into wayfinding (the cognitive process related to navigation) and travel (the actions executed to reach a destination). Travel can be further divided into: exploration (roaming with no explicit goal), search (there is a specific goal), and maneuvering (small displacements, precise control of the viewpoint required).

Natural walking stands as the most natural and effective navigation technique [25, 36], not involving additional controls and leveraging our oculomotor control and vestibular systems, with positive effects to understand the environment [5]. However, this method of locomotion is only feasible when the 3D world is (at most) as big as the working volume of the tracking system. Hybrid approaches complement walking with other techniques, such as joysticks to travel in specific directions [4], or controllers to teleport to other locations (e.g. commonly used in HTC Vive games). However, joysticks create the feeling of flying rather than walking [19], and teleportation hinders navigation skills [7].

Redirected walking techniques exploit change blindness [22], giving the illusion of naturally walking a large VE while keeping users within the tracking volume. Techniques proposed make use of rotational gains [24], translation gain [39], space substitution [32] or distractors [23]. However, the tracking spaces needed are still large (e.g. 6.5x6.5m in [22]).

Walking in place (WIP) techniques also involve physical displacement (i.e. navigation controlled by the movements of the user's body), but with no actual translation of the user. Thus, users simulate walking, and the movement of their feet [27], heels [8] or knees [38] is used to control translation in the VE. These techniques have also been adapted for mobile VR devices [35] and seated environments [34]. Although regarded as immersive and natural [27], WIP techniques do not provide the same vestibular cues than walking (e.g. no inertia). Delays in detecting the start/stop of the motion can also affect presence [33] and encumber maneuvering [8].

Hardware solutions using linear [29] or omnidirectional treadmills [6], or with the user walking inside a rotating sphere [9], provide a closer match to natural locomotion. However, they still do not produce the same proprioceptive perception as real walking [1, 37]. The need to deploy a bulky and expensive hardware element in the users' home can also limit their adoption.

Steering techniques loosen the role of body motion. They use the direction of the user's head [11], torso [17] or hands [2] to determine direction of motion, but require of additional control commands (e.g. joysticks, gestures) to trigger motion or determine speed. Solutions using joysticks, gamepads or mouse and keyboard have also been extensively user (e.g. games), but they negatively influence spatial orientation [16] and the sense of presence [36].

Dynamic control of the viewpoint

Dynamically scaling the translation speed of the viewpoint has been mostly applied for less immersive navigation techniques (i.e. not involving physical displacement).

Mackinlay et al. [21] is one of the pioneering techniques, with some similarity to the *NaviFields* technique. When a user selects a target destination, a logarithmic function allows fast displacements along big distances, progressively slowing down as the user reaches the destination. Argelaguet [26] allows open-ended navigation (not based on selection of a target destination), but uses the optical flow in the user's view to adjust the navigation speed based on the user's perception of motion. Lecuyer et al [4] use a model of the head's lateral motion, rotation and eye fixation, affecting viewpoint motion to improve the sensation of passive walking in the VE. In these techniques, motion speed is not connected to the meaning/relevance of the objects in the environment. Freitag et al. [10] adjust travel speed based on viewpoint quality (i.e. how informative a viewpoint is), sharing some conceptual similarity with our approach.

The dynamic modification of viewpoint scale and speed is much more uncommon for VR techniques involving physical displacement, as these are mostly focused on providing a 1:1 mapping between the user's real and virtual displacements.

Redirected walking techniques have made use of subtle changes in scaling, to alter users' paths without translation gains becoming noticeable [30]. Multi-scale techniques scale the size of the user (rather than its speed), to interact with the VE at microscopic or macroscopic levels [15].

Use of higher scaling factors to navigate bigger spaces have been even less common. Williams et al. [39] scale user's physical displacement using a constant scaling factor. Interrante et al [13] couple the scaling factor, to the speed of the user's real head. While allowing close to natural navigation at low speeds, the viewport will move exponentially faster, the faster the user moves in reality. LaViola et al. [18] use their feet to interact with a World-In-Miniature (WIM) [1]. Little displacements on the WIM cause large displacements of the user, and scale can also be adjusted with foot gestures. In all these cases, viewport speed is controlled by users' actions alone (egocentric), and not by the contents of the VE (allocentric, as in *NaviFields*).

The closest match to the proposed *NaviFields* technique can be found in [28]. This technique identifies a sphere in the VE, describing the primary space for interaction. Natural navigation is available inside the inner sphere, but motion is scaled exponentially outside this sphere. Like *NaviFields*, this allows for bigger navigable spaces, using physical displacements and with scaling being driven by the structure of the VE (i.e. allocentric, instead of egocentric). It can thus be considered as a particular instance of the fields our technique covers, but it does not deal with the interactions among several areas and cannot address the relevance of each point of the VE individually.

NAVIFIELDS: ADAPTIVE VR NAVIGATION

NaviFields uses the known location of the interactive areas within the VE, enabling natural 1:1 navigation within those areas, while gradually speeding up displacements when travelling between interactive areas. In practice, this increases the navigable space, retains a physical displacement metaphor in all the VE and 1:1 natural displacement in places demanding precise navigation (maneuvering) or interactive tasks (precise manipulation).

The following sections describe the mathematical modelling of the adaptive navigation and the description of the *navigation field* (that determines the scaling applied at each point of the VE). For our explanations, systems of reference will be noted as capital letters, with **U** referring to the user's head system of reference; **T** referring to the system of reference of the tracking system; and **W** referring to the system of reference of the virtual world. We will make use of right hand systems of reference, homogeneous coordinates (i.e.points in A's coordinates as $\boldsymbol{P_A}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z},1) \in \mathbb{R}^4$) and 4x4 matrices ($\boldsymbol{M_B^A} \in \mathbb{R}^{4x4}$, to convert coordinates from A to B). This notation will aid reproducibility and ease explanation of our technique in comparison with homogeneous scaling .

Modelling Navi-Fields: Differential tracking

Physical displacement techniques usually rely on a bijective mapping between the real space (tracking volume) and the navigable space in the VE. In other words, each point in the real world is uniquely mapped to a point in the VE and vice-versa. Our technique breaks this bijective mapping in order to dynamically scale displacements according to the location of the user (inside an interactive area or a transition area).

This can be illustrated comparing *NaviFields* to the use of a homogeneous scaling factor [39] (shown in Eq(1)). In this technique, the position of the user's head at any specific point in time $\boldsymbol{M_T^U(t)}$ is scaled by a constant scale matrix $\boldsymbol{S(k,1,k)}$, effectively increasing the navigable space in the XZ plane by a factor of $k \cdot k$ (see Figure 2, A&B). Finally, this scaled navigable volume is mapped to a specific part of the virtual world using a constant transformation $\boldsymbol{M_W^T}$ (i.e. teleporting can be implemented by dynamically modifying M_W^T.

$$\boldsymbol{M_W^U}(t) = \boldsymbol{M_W^T} \cdot \boldsymbol{S}(\boldsymbol{k},\boldsymbol{1},\boldsymbol{k}) \cdot \boldsymbol{M_T^U}(\mathrm{t}) \qquad (1)$$

This mapping is invertible, showing a bijective mapping between spaces **W** and **T**:

$$\boldsymbol{M_T^U}(t) = \boldsymbol{S}(\boldsymbol{k},\boldsymbol{1},\boldsymbol{k})^{-\boldsymbol{1}} \cdot \left(\boldsymbol{M_W^T}\right)^{-\boldsymbol{1}} \cdot \boldsymbol{M_W^U}(\mathrm{t}) \qquad (2)$$

In contrast, our approach relies on the previous position of the user's head and is not directly invertible. At each point in time, the current position is computed from the previous virtual position $\boldsymbol{M_W^U}(t)$ and the current real displacement of the user's head (Eq. (3)). This displacement is scaled by a variable factor $\boldsymbol{k}(\boldsymbol{M_W^U}(t))$, which depends on the location of the user in the virtual world (Eq. (4)). Orientation (direction) of motion is not affected. This function relating the virtual location of the user to displacement represents our *navigation field* and is explained in the following section, being a key element for the adaptive nature of our technique.

$$\boldsymbol{M_W^U}(t+dt) = \boldsymbol{M_W^U}(t) + \boldsymbol{D}\left(\boldsymbol{k}\left(\boldsymbol{M_W^U}(t)\right)\right) \cdot \frac{d\boldsymbol{M_T^U}(\mathrm{t})}{dt} \qquad (3)$$

$$\boldsymbol{D}\left(\boldsymbol{k}\left(\boldsymbol{M_W^U}(t)\right)\right) = \boldsymbol{S}\big(\boldsymbol{k}(\boldsymbol{M_W^U}(t)),\boldsymbol{1},\boldsymbol{k}(\boldsymbol{M_W^U}(t))\big) \qquad (4)$$

The initial location of the viewpoint is defined as in Eq.(5), mapping the navigable volume to a specific part of the VE:

$$\boldsymbol{M_W^U}(0) = \boldsymbol{M_W^T} \cdot \boldsymbol{M_T^U}(0) \qquad (5)$$

Generating the navigation field $\boldsymbol{k}(\boldsymbol{M_W^U}(\boldsymbol{t}))$:

The previous section described the adaptive technique enabling variable displacement according to the user position in the VE. However, it is still necessary to define the *navigation field*, that is the scalar field $\boldsymbol{k}(\boldsymbol{M_W^U}(t))$ describing the scaling factor to apply at each point of the VE.

Being a scalar field, navigation fields can be represented as textures, with the value of each pixel describing the scaling factor to apply (and we will represent them as such throughout the paper). However, here we describe a general approach to automatically compute this *navigation field*

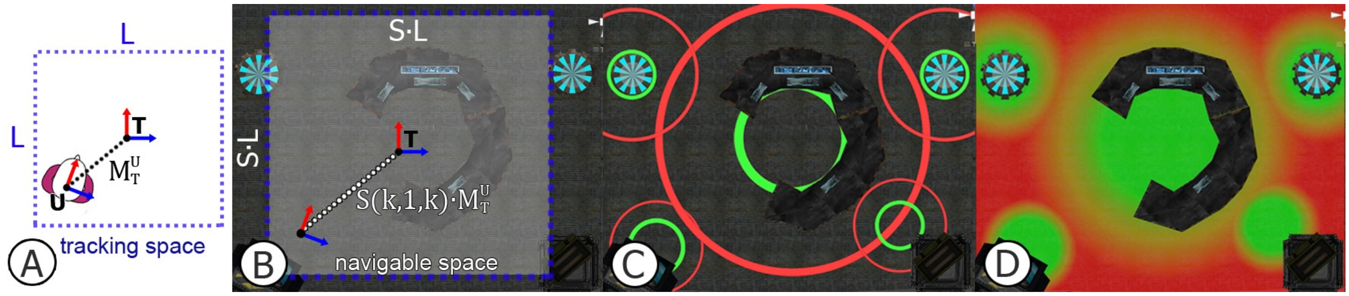

Figure 2. (A) Tracking spaces are usually reduced. (B) Physical displacement with homogeneous scaling can increase the navigable volume by a constant factor S. (C) In NaviFields, each interactive area provides a different scaling function, based on how relevant each point is to interact within that area. (D) We compute the final *Navigation Field*, by combining these individual contributions.

based on a set in interactive areas. To do so, we first model the contribution of each interactive area and then compute the final field from these individual contributions.

Per interactive area contribution:

For each interactive area, we compute a simple function that describes the scaling to be applied to a user position, based on how relevant that position is to interact in that area. Let $\boldsymbol{I}$ be our set interactive areas in the world (**W**). We model each area $\boldsymbol{i} \in \boldsymbol{I}$ as a tuple $\boldsymbol{i} = \{i_W, r_i, R_i, M\}$, representing two concentric cylinders of radii r_i and R_i centered around $i_W \in \mathbb{R}^4$, and with maximum scaling factor M (see Fig 3.A).

Let $\boldsymbol{P_W} = \boldsymbol{M_W^U}(t) \cdot (0,0,0,1)^T$, be the current position of the virtual head and $\boldsymbol{P'_W}$ its projection on the horizontal plane (Y=0). We define contribution of area $\boldsymbol{i}$ to the field as in Eq. (5), where $d = \|\boldsymbol{P'_W} - \boldsymbol{I_W}\|$ represents the distance between the user and the center of the interactive area:

$$\boldsymbol{k_i}(\boldsymbol{P'_W}) = \begin{cases} 1 & , d \le r_i \\ 1 + (\boldsymbol{M} - 1) \cdot \dfrac{d - r_i}{R_i - r_i} & , r_i < d \le R_i \\ \boldsymbol{M} & , R_i < d \end{cases} \quad (5)$$

This function provides no scaling ($\boldsymbol{k_i}(\boldsymbol{P_W}) = 1$) inside the inner cylinder, to facilitate maneuver and precise interaction. The scaling factor increases linearly between the inner and the outer cylinders, to ease navigation to distant points. It must be noted that, although this function shows a linear behavior, it operates on the user's velocity ($d\boldsymbol{M_T^U}(\mathrm{t})/\mathrm{dt}$, in Eq. (3)). Thus, user moving away from $\boldsymbol{i}$ at constant speed will actually experience a parabolic motion. This is inspired from related approaches of viewport control [21], to reduce simulation sickness [20] and maintain spatial awareness [2].

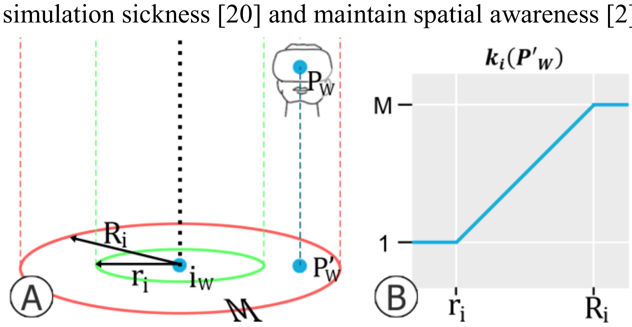

Figure 3. (A) Interactive areas are defined by their inner and outer cylinders (radius r_i and R_i) and their maximum scaling factor M. (B) Function described by each interactive area.

Global navigation field:

Each area $\boldsymbol{i} \in \boldsymbol{I}$ provides a different scaling function, based on how relevant each point is to interact with that area. Thus, for given a point $\boldsymbol{P_W}$, each area will provide a different scaling factor. We resolve conflicts by describing the *navigation field* as the minimum scaling factor across all interactive areas (see Eq. (6)). This ensures natural navigation inside all interactive areas ($\mathbf{k}(\boldsymbol{P_W}) = 1$). User motion will also be speed up when leaving an interactive area and slowed down again when arriving to a new area.

$$\boldsymbol{k}(\boldsymbol{P_W}) = \min\{\boldsymbol{k_i}(\boldsymbol{P_W})\}, \boldsymbol{i} \in \boldsymbol{I_W} \quad (6)$$

It must be noted that all the definitions provided in this section only scaled displacements along the horizontal plane (assumed XZ). This is convenient for most indoor VEs and avatars resembling humans. In other application contexts (e.g. a spaceship game, where head physically controls motion of the ship) scaling factors $\boldsymbol{k}$ and $\boldsymbol{k}(\boldsymbol{M_W^U}(t))$ should also affect the Y coordinate. Similarly, volumetric textures should be used to represent these such *navigation fields*.

USER STUDY

The previous sections motivate the need for *NaviFields* and provide a formal definition for the technique. In this section we assess the usability of the navigation technique for search travel and maneuvering (low-level navigation tasks [1]).

We compare our technique to the use of homogeneous scaling [39], rather than other scaled physical displacement approaches [10, 18], as these later ones impose an egocentric approach that does not match the inherent allocentric nature of *NaviFields* (i.e. scaling controlled by the environment, not the user). Rather than focusing the study on egocentric vs allocentric navigation, we include an additional comparison to natural navigation. This baseline comparison, and the extensive analysis of the factors influencing search and maneuvering (scaling factors, path lengths, maneuvering complexity and user poses), allow us to present a full testbed evaluation on the particularities of the technique proposed.

Participants

We performed our study across two different European countries (Spain and UK). Both locations used equipment with similar performance (90fps) and an empty experimental space of 3x3m for navigation. We used written in-game instructions in both languages to guide participants' training,

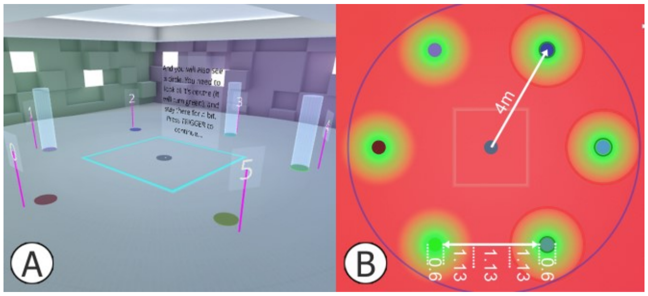

Figure 4. (A) Screenshot of the test environment implemented, with six target flags around initial location. (B) The *navigation field* was computed for each condition, and used to compute the equivalent homogeneous scaling factor.

to minimize differences across countries (i.e. different experimenters providing the instructions) and to reduce bias due to such oral instructions. Following this process, we recruited 24 participants (12 in each country), collecting written consent from them before the start of the experiment.

Testing environment and Navigation Tasks

We implemented our technique[1] using Unity, and a HTC Vive headset, and created a testbed environment to evaluate it (Figure 4A). The environment contained six target areas of 60cm Ø, identified with numbered flags and evenly distributed around the user's initial position.

Participants were invited to stand in the center of the experimental space, wearing the headset and holding one of the HTC controllers. At the beginning of the experiment, users went through a short in-game walkthrough, to familiarize with the virtual environment and the tasks. They also performed one travel task (using natural navigation) and one maneuvering task (see the next section) for training.

For the following trials of the experiment, participants performed a two part task, the first part to test the usability of the techniques for travelling, and the second one focused on maneuvering.

Travelling Task:

At the beginning of each trial, users were positioned in the center of the tracking space (and aligned to the center of the VE). A text box was then displayed in front of them, describing a sequence of flags they had to travel to (target flags). Target flags appeared highlighted (see Figure 4A). Participants were allowed to look around to identify the flags (for planning and wayfinding). When ready (and only if still standing inside the central area) users pressed the trigger on the controller, to start the task and travel towards the flags. The task finished when the user reached the final flag.

Maneuvering task:

When participants reached the last flag in the travelling task, an audio signal notified them of the start of the maneuvering task. We then used an adapted version of in-world ParaFrustum [31] (see Fig 5.A) to describe the maneuvering task. Participants had to attain and keep a correct head position and orientation for one second, to complete the trial.

[1] To be published at Unity Asset Store (under review).

In our adaptation, two spheres (red for the left eye and blue for the right eye) showed to the users where they had to position their eyes (size of the spheres reflected the positioning tolerance allowed). After positioning, a green ring (tail/target, in the ParaFrustum notation) identified where users had to look at. A small cursor helped users to align their view to the target. The size of the ring was computed based on the maximum orientation error allowed. Thus, if the cursor was inside the ring, the orientation error would be small enough. Please note that this differs from the original ParaFrustum proposed in [31], where the ring is shown at the periphery of the vision field. While this might be appropriate for the field of view (FoV) of the device they used (~60 deg), the wider FoV in the Vive pushed us to use this alternative implementation (i.e.to keep attention focused on the target to look at, instead of on the periphery of vision).

In each maneuvering trial, six ParaFrustum's were displayed in six potential positions around the flag, arranged in a hexagonal pattern (see Fig 5B). These forced three different poses in the users: kneeling (maximum stability, but reduced mobility), medium (low stability, higher mobility) and standing (good stability and mobility).

Self-report:

At the end of each trial, participants were asked to answer 4 questions. Two inquiring how easy/comfortable it was to walk to the flags (i.e. travel task) and two inquiring how easy/comfortable it was to look at the targets (i.e. maneuvering task). Questions were displayed either in English or in Spanish on floating textboxes. Each question used a Likert scale from -3 to 3, which participants selected by moving the controller on their choice and pressing trigger.

Experimental design

Travelling task:

In the experiment, we compared the proposed *NaviFields* technique (NF) to Physical Displacement with a homogeneous scaling factor (PH). We adopted a 2x3x2 full factorial design, with these factors being the condition tested (T={NF, PH}), the scaling factor used (S={2, 4, 8}), and the lengths of the travelling path (between L=3 or L=5 flags, see travelling task above). Scaling factors were selected based on a pilot study with 8 users, where S=16 was found too high.

Experimental trials were pseudo-randomized using Latin Squares, counterbalancing order among participants according to technique, scaling factor and path length. That is, trials were presented within 2 blocks of six trials each (one block per NF or PH condition). These six trials then counterbalanced scaling factors (S={2, 4, 8}, S={4, 8, 2} or S={8, 2, 4}) and path lengths (L={3, 5} or L={5, 3}).

After the two condition blocks, participants completed a third block with natural navigation (S=1), which was used as a control condition (most natural and with most experience from the user). This will allow us to express our results as a deviation from a baseline, comparing performances in PH and NF as deviations from the optimal/baseline condition.

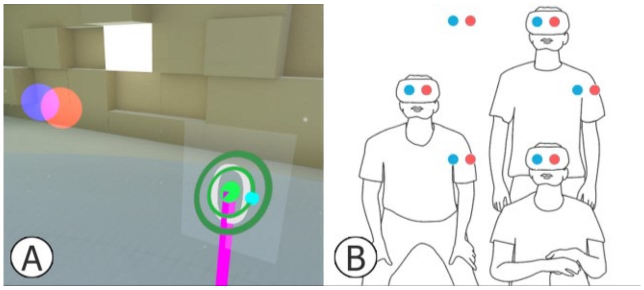

Figure 5. (A) Screenshot of the in-world ParaFrustum implemented. (B) ParaFrustums were randomly located among 6 potential locations, each enforcing a different pose of the user

Using this approach, we maintained our experimental design balanced and fully factorial. An alternative would have been to add a fourth scaling factor (S=1) to the design. However, when S=1, NF and PH behave in the same way. Thus, trials with S=1 would be performed twice more than any other trial. Also, removing S=1 in either NF or PH would have resulted in an unbalanced experimental design.

Finally, we made sure that, while the starting flag for each travelling task was randomly selected, the total distance to travel between flags was always equal for all trials under the same L condition. In other words, all paths with L=3 had the same length, as well as all paths with L=5. Up to 24 paths of equal distance were identified for L=3, and 108 paths for L=5, with paths being randomly selected for each trial.

Maneuvering Task

The maneuvering task was performed at the end of each travel task. Given the experimental design explained above, each maneuvering task was repeated twice for each scaling factor and condition (i.e., for any given S and T, there is one maneuvering trial with L=3, and second one with L=5). This allowed us to test twelve different ParaFrustums per scaling factor and condition. The twelve ParaFrustums were a combination of three different factors, namely the ParaFrustum's position (P), head size (HS) and tail size (TS).

Position (P={KP, MP, SP}) was connected to the location of the ParaFrustum (see Fig 5.B) and represented the user pose than allowed him/her to reach the eye spheres, either kneeling (KP), medium (MP) or standing (SP).

Head size (H_S={TH,LH}) related to the position error tolerance of the ParaFrustum. That is the size of the red and blue spheres indicating to the users where to position their eyes. Two sizes were compared: Tight head (TH; $\pm$1.5 cm max eye position error) and Loose head (LH, $\pm$ 3cm).

Tail size (T_S = {TT, LT}) related to the orientation error allowed by the ParaFrustum and was visually connected to the size of the target ring. Two sizes were tested: Tight tail (TT; max orientation error $\pm$5 degree) and Loose tail (LT, max orientation error $\pm$10 degrees).

Scaling factors, Environment size and Navigation Fields

To test navigation across bigger virtual environments, the distance of the flags to the center in the virtual environment increased proportionally with the scaling factor (S). More specifically, flags were located at D_S=*{2m, 4m, 8m}* from the center respectively for each S={2,4,8}. For the baseline condition (natural navigation) flags were located at D_1=*1m* from the center of the VE.

The configuration of the interactive areas (the flags) also changed according to the scaling condition S. All areas $\boldsymbol{i} \in \boldsymbol{I}$ maintained an inner radius $r_i = 30$ cm (60cm Ø), but their outer radius was set to $R_i = r_i + (D_S - 2r_i)/3$. For two adjacent flags, this outer radius covered one third of the distance between the edges of their inner 1:1 areas (Figure 4.B shows an example for S=4, with specific measurements in meters). Thus, independently of the scaling applied, a user travelling between adjacent flags would go through the transition zone of the first flag for one third of the trip, through the area of maximum speed during the second third, and into the second flag's transition zone in the last third.

Finally, the scaling factors (S) needed to be compensated across techniques. For example, a scaling factor S=2 in PH would apply in all the navigable space. However, if we used M=2 in the interactive areas (see Eq(5), for the meaning of M), this scaling would only apply when users are outside of all interactive areas (i.e. red areas in Figure 4B).

To balance these conditions for each S factor, the interactive areas will use an M value that provides an average scaling across the *navigation field* equal to our target value S. To compute these equivalent M values, we simply configured the areas as described above (distance to center D_S, inner and outer radius values). We then performed a linear search, testing increasing M values until the average scaling factor (i.e. integral of the *navigation field* divided by area) matched our target value S. Using this approach the equivalent M values to use for each S{2,4,8} were M={2.19, 4.60, 9.17}. Note that these values need to be slightly higher than PH, to compensate for the areas where no scaling is applied.

Usability evaluation criteria

The experimental software automatically recorded several dependent variables. For the travelling trials these were: task completion time (T_TCT), real distance travelled (T_RD) and deviation (T_D). T_TCT measured the time since the participants arrived to the first flag until they reached the final flag. T_RD measured the distance users moved their head (in reality). Finally, T_D measured the ratio between length of the virtual trajectory followed (linear integral along the path) divided by the optimum/minimum path length.

For maneuvering, the variables recorded were: task completion time (M_TCT), number of fixation attempts (M_FA), average position error (M_PE) and average orientation error (M_OE). M_TCT measured the time required to complete the task. The task required users to stay within the constraints of the ParaFrustum continuously during one second. Leaving it, even for one instant would reset our one second timer. The number of fixation attempts (M_FA) counted the number of times this happened.

Average position error (M_PE) and average orientation error (M_OE) measured error only while the user's was correctly located within the ParaFrustum constraints.

Finally, we collected the responses to the four questions as Q_CT, Q_ET, Q_CM and Q_EM, to refer to the ease (E) and comfort (C) for the travel (T) or maneuvering task (M).

RESULTS AND PARTIAL DISCUSSION

In this section, we report the results of our user study. Independent sample t-tests across countries showed no significant differences. During our joint analysis of travel, maneuver and self-reports, we used within-subjects analysis of variance (ANOVA) to analyze the impact of each factor on the dependent variables (explained above). We also measured interactions between technique (T) and the other independent variables in the task (e.g., interactions between condition T and variables L and S, for the travelling task).

Please note that the reported values (average and standard deviation) are reported as **deviations from baseline (natural navigation)**. Given the high number of features examined, and because of the nature of the results (many significant interactions between variables), we will only report the absolute results in the supplementary material. Were needed, post hoc analysis with Bonferroni corrections were performed and most of them can be found in Figures 5 and 6 (i.e. significance between pairs is indicated with an asterisk; and the difference between the pairs can be assessed from the graphs itself). The average and standard deviation of the baseline is also included in a box under the horizontal axis of each graph (i.e. to help assess the relevance of the effects observed between conditions). Numerical reports, absolute averages and standard deviations (instead of deviation from baseline) and average and standard deviation indicating the exact values of factors in the significant interactions can be found in the supplementary material.

Traveling task: NaviFields vs. Homogeneous Scaling

ANOVA results for travelling are reported in Table 1, both for the main effects and their interactions with T.

Both techniques behaved on average worse than the baseline (see Figure 6A) in terms of deviation from the optimal path (T_D). Lateral movements of the head while walking could justify this, as these were scaled by both techniques. So, even if the torso was moving linearly (following the optimum path), the sinusoidal side movement of the head would be scaled, resulting in higher distance travelled and worse T_D.

However, our technique (NF) showed much lower deviation than homogeneous scaling (PH), with this difference becoming more relevant for higher scaling factors (significant interaction T*S). Paired analysis (indicated with asterisks in Figure 6) reveal differences between NF and PH are significant under all scaling conditions. This could be the result of head side displacements being scaled less while the user travelled through low-scaling parts of the virtual environment (inner areas and transition zones). It is also worth noting that NF was only significantly worse than the baseline for S=8 (paired t-test, Bonferroni corrected, p<0.05), indicating that for lower factors, users could still follow their paths effectively.

	T	S	L	T*S	T*L
T_D	F=29.53 p < 0.001	F=43.45 p < 0.001	F = 3.04 p= .093	F = 8.13 p< 0.001	F= 0.45 p = 0.50
T_RD	F= 111 p< 0.001	F= 98.62 p< 0.001	F= 78.74 p< 0.001	F=78.68 p< 0.001	F=23.44 p< 0.001
T_TCT	F= 0.229 p = 0.63	F=76.96 p< 0.001	F= 73.9 p<0.001	F=2.10 p = 0.13	F= 0.22 p = 0.63
CT	F= 6.646 p< 0.05	F= 32.03 p< 0.001	F= 0.404 p= 0.531	F= 1.182 p= 0.315	F= 0.026 p=0.87
ET	F= 15.8 p< 0.001	F= 31.75 p< 0.001	F= 2.229 p= 0.14	F= 0.904 p= 0.412	F= 0.036 p= 0.851

Table 1. Results from repeated measures ANOVA on travel-related features and questionnaire ratings(CT and ET rows). Effects of technique (T), scaling (S) and path (L), as well as interactions among them (T*S, T*L)

On average, users also moved more in the real environment (T_RD) with NF and PH than in the baseline condition (see Figure 6B). The difference between PH and baseline can be explained by looking at our users' behavior. Paths were equivalent for PH and baseline if users passed through the center of the interactive areas. However, as soon as users reached the inner radius of the area, a sound was triggered, and most users directly proceeded to the next flag (travelling between the *edges* of the areas). Thus, using PH with scaling S=4, the 60cm interactive area would be reduced to 15cm in the real world (with users traveling 22.5 cm more to reach *edges*). Considering the distances between flags from Figure 4B, this led to a final travel distance of 339cm/4 = 85cm.

This situation was even worse for NF. Using the same example (and measurements from Figure 4B), users would require 40cm to travel through both transition areas, and 25 cm to go through the area of maximum scaling, resulting on a required total distance of 105cm. These differences in the distances required for each technique actually increased with higher scaling factors, further penalizing the NF condition.

The fact that participants moved more in the real environment in both NF and PH can also help explain why users took more time to travel (T_TCT) in the two conditions (see Figure 6C), and the influence of S and L.

However, we found the lack of significant differences between NF and PH in terms of T_TCT interesting. We actually expected *NaviField* to behave worse than PH, given that: **a)** the user was not in control of the velocity (depends on his position in the VE); and **b)** bigger S and L values should have penalized the NF technique even more than PH in terms of T_RD. The most likely way NF users could cover more real distance in (not significantly) higher time, would be if they actually moved faster in reality, which would indicate a higher level of confidence during locomotion.

Questionnaire results also aligned in this direction, showing a general preference for NF (significance of T, for both C_T and E_T), which was further reinforced at higher scaling factors and distances (interaction T*S, and T*L for both C_T

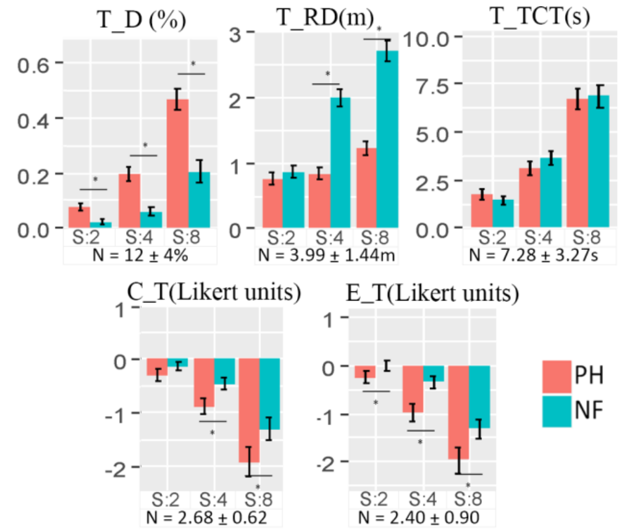

Figure 6. Barplots representing mean and standard error of the variables collected in the travelling task, for each condition and scale factor. Significant post-hoc tests (p<0.05) between condition at each level of scaling are marked with *.

and E_T). Particularly, for all factors higher than S=2, travel was considered easier in NF and also more comfortable (see significant post-hoc tests in Figure 6, for C_E and E_T). The fact that human motor control is planned in advance, based on the information collected from the environment [12, 14], could also influence the better performance and preference for NF. Despite both NF and PH scaling users' movements, we observed participants using NF tended to look around to plan the travel trajectory before starting locomotion (e.g. while inside a 1:1 area). The progressive increase in scaling could also have helped them to tune and adapt motion, once travelling started. These factors could help participants in the NF condition perceive travel as more comfortable. Finally, the progressive slow down when reaching the flags could serve as a feed-forward, reassuring them on the successful completion of the task, before actually finishing it.

Maneuvering: NaviFields vs. Homogeneous Scaling

Table 2a reports the main effects from the ANOVA model for the independent variables, while Table 2b reports the main effects for all the interactions. Table 2c reports ANOVA results for the maneuvering questionnaires.

Our results clearly show *NaviFields* (NF) provided better results than PH for maneuvering. Significant effects were found for all variables (with NF always performing better). Also, higher scaling factors increased these differences even more (note the significant interactions T*S according to all variables; diverging trends clearly observable in Figure 6).

These results were expected. For instance, in the case of a small ParaFrustum head (3cm) and S=4; participants using PH had to place their head within a sphere of 0.75cm. When compared to baseline, PH was significantly worse for S factors bigger than 2 (p < 0.05 for all post-hoc tests between scaling and baseline; see supplementary material).

	T	S	H_S	T_S	P
M_TCT	F= 185.7 p < 001	F=103.7 p< .001	F= 09.7 p< 0.001	F=5.332 p < 0.01	F = 10.9 p< .001
M_OE	F=41.27 p <.001	F=19.77 p <.001	F = 1.35 p = 0.25	F =9.282 p < 0.001	F=0.295 p = 0.59
M_PE	F= 12.99 p < 0.01	F= 7.39 p< 0.01	F= 5.866 p< 0.05	F= 0.115 p = 0.07	F= 0.017 P = 0.89
M_FA	F= 267 p < 0.001	F=134.8 p< 0.001	F=97.81 p< 0.001	F = 0.629 p =0.43	F = 9.586 p < 0.05

Table 2a. ANOVA effects for each independent variable.

	T*S	T*H_S	T*T_S	T*P
M_TCT	F= 140.2 p< 0.001	F=97.25 p< 0 .001	F= 2.54 P = 0.124	F=13.59 p< 0 .01
M_OE	F=17.5 p <0.001	F=5.64 p <0.05	F=0.64 p =0.4	F=0.002 p = 0.96
M_PE	F= 5.08 p< 0 .001	F= 2.20 P=0.1	F= 6.459 p< 0.05	F= 7 p< 0.05
M_FA	F = 174.3 p< 0.001	F = 125.3 p< 0.001	F = 2.02 p = 0.16	F = 8.5 p < 0.05

Table 2b. ANOVA effects for the interactions of the factor T with dependent variables for maneuvering

	T	S	L	T*S	T*L
CM	F= 82.84 p< 0.001	F= 47.18 p< 0.001	F= 3.194 P= 0.08	F= 77.33 p< 0.001	F= 3.135 P=0.08
EM	F= 60.15 p< 0.001	F= 39.73 p< 0.001	F= 0.59 p= 0.44	F= 42.97 p< 0.001	F= 4.17 P = 0.052

Table 2c. ANOVA effects for questionnaire questions and interactions of factor T with each of the remaining variables.

In contrast, NF enables similar amount of control than natural navigation. Indeed, when comparing NF to the baseline, no significant effect of scaling or condition was found for any of the variables, including questionnaires (CM and EM). Although expected (NF allowed close to 1:1 navigation during maneuvering), these results clearly illustrate one of the main strengths in NF (allow larger navigable spaces, but still allow precise maneuvering), and also show the impact scaling can have on maneuvering tasks.

Besides, our study also revealed some other relevant aspects related to maneuvering tasks, which can be applied to *NaviFields*, or any other physical displacement navigation techniques scaling user's motion [13, 28, 30, 39].

First, these results seem to challenge related work, were a homogeneous scaling factor of S=10 was regarded as still comfortable for users [39]. Results from both travel and maneuvering show a clear decrease in performance as scaling factors increase. The precision demands of the task also have a great influence on this factor (i.e., more significant effects in our maneuvering results).

However, it was interesting to observe that users seemed to have a relatively good maneuverability with a scaling factor of 2, both for NF and PH. In this condition (S=2), no significant differences could be observed between PH and NF (or baseline) in terms of M_OE and M_PE (observe lack of differences between pairs in Figure 6, for S=2). Questionnaires further reinforced this observation: for S=2 no significant difference were found between NF and PH (t < 1 and p > 0.05), for both CM and EM.

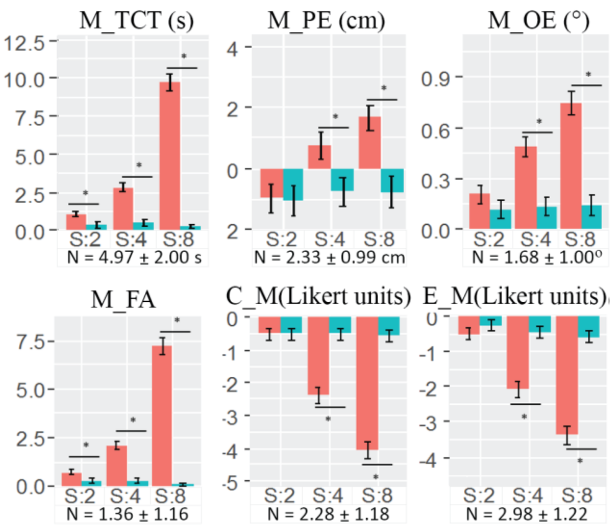

Figure 7. Barplots representing mean and standard error of the variables collected in the maneuvering task, for each condition and scaling. Significant post-hoc tests (p<0.05) between condition at each level of scaling are marked with *.

This seems to indicate that, even in precise tasks, users can adapt their movement to finely control their gaze and posture, even in conditions where their visual feedback is dissociated from their proprioceptive and vestibular feedback by a factor of 2. This could encourage the use of scaling factors bigger than one even inside relevant areas. This could further increase the additional navigable space while not affecting interaction significantly.

Our results also seem to indicate that, when scaling was applied, maneuvering complexity was mostly driven by the position error allowed by the ParaFrustum (rather than the orientation error). It is worth noting that ParaFrustum head sizes chosen (H_S={3cxm, 6cm}) had a significant effect on M_PE (less error for loose head sizes). The same applied to tail size (T_S={±5˚, ±10˚}), with main effect on M_OE (again, less error for loose tail sizes). These results indicate that the sizes and angular ranges chosen actually represent two positioning and two orientation tasks with different levels of complexity. However, the influence of H_S (Effect size on M_OE, Choen's d=0.23) was much bigger than T_S (Effect size on M_OE, Choen's d=0.5). This relevance of positioning vs orientation should be specially considered when designing tasks for points of the VE with higher scaling factors (for S>2, allow more positioning error).

Finally, the user's pose had significant effects on the time (M_TCT) and number of attempts required (M_FA). Trials completed standing had on average the best performance and, surprisingly, kneeling led to the worst performance (higher M_PE, M_TCT, M_FA, M_OE, when compared to other poses). This seems to indicate mobility range can become a much more relevant factor that stability, for maneuvering in environments using displacement scaling. We observed that, the small movement of the participants' head while kneeling (down, but also forward) was scaled up, and users would tend to move past their target location. Users had to learn and anticipate this, either avoiding forward motion while kneeling, or by kneeling at a further distance to the target. This made it more difficult to reach the desired position, and the more limited range of motion of the pose, also offered less chances to correct it. Thus, users needed several attempts before "landing" in the correct spot.

DRIFTING EFFECTS IN NAVIFIELDS

Another observed effect from our studies was the presence of drift in our technique. That is, a participant returning to the center of the VE, would not actually end up in the same position where he started in the real world. Being an unforeseen effect, our software did not collect data as to allow us to provide an empirical assessment of its impact. However, this effect did not result in any major issues during our experiments.

The effect of drift can be exemplified by Figure 8, left. This shows a user walking in a closed trajectory near an interactive area with r_i= 1m, R_i= 3m and maximum scaling M=3. In reality (right side of the Figure), this user would walk 1m across the inner area (arrow *a*) and 1 m across the transition area (arrow *b*; average scale of two). Due to scaling, the curved trajectory in (*c*), would require an arch in reality of only 3/3=1 m of radius, but in the path back to the center (*d* and *e*, similar to *b* and *a*), our example user would end up 1.41 m away from the starting point.

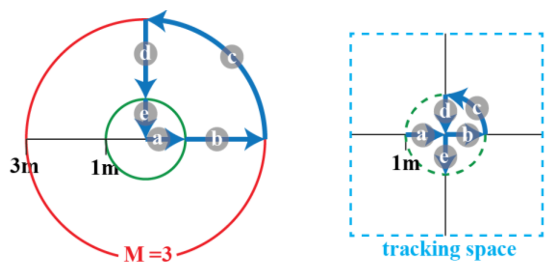

Figure 8. Example of the role of drift. A user walking along a closed path in the VE, will not return to the same real point.

This effect is the result of the different scales used for motion in the virtual and real world. For any given closed path A, the drift vector can be computed as in Eq(7) (a full derivation for Eq(7) is available in the supplementary material).

$$Dr(A) = \int_0^A \boldsymbol{S}\big(\boldsymbol{k}(\boldsymbol{M}_W^U(t) - 1\,, 0\,, \boldsymbol{k}(\boldsymbol{M}_W^U(t) - 1)\big) \cdot \frac{dP_T(t)}{dt} \cdot \boldsymbol{dt} \quad (7)$$

Once modelled, this effect can be addressed by borrowing approaches from redirected walking. For instance, the drift accumulated by the user since the beginning of the session is implicitly represented by the difference between its virtual and real positions ($\boldsymbol{M}_W^U(t)$ and $\boldsymbol{M}_T^U(t)$). However, the effect of the drift cannot be assessed until the user returns to the original position (he/she closes the path). One simple approach is to, at every point in time *t,* compute the drift that would be present if the user wished to return to the starting position, (following a linear path L from $\boldsymbol{M}_W^U(t)$ to $\boldsymbol{M}_W^U(0)$):

$$Dr(A') = \left(\boldsymbol{M}_W^U(t) - \boldsymbol{M}_T^U(t)\right) + Dr\ (L) \qquad (8)\ \text{-}$$

This estimation can now be used to iteratively reduce drift. If the current displacement (Eq(4)) will increase the magnitude of the drift vector, one could positively scale this displacement (i.e. so that the user continues to move in that direction for as short as possible). Alternatively, if the current displacement will reduce drift, user motion should be damped (i.e., to force motion in drift-correcting directions).

DISCUSSION

The results from our experiment have shown very good potential of *NaviFields* as a navigation technique, allowing users to navigate environments up to 8x8 times bigger than natural navigation, with very good potential for both travelling and maneuvering. However, its effects on higher level aspects on navigation (spatial orientation, way-finding, presence, cyber-sickness) should still be assessed.

Other aspects revealed by our study also deserve further exploration. Reusing models to predict body motion from head motion [4, 10, 27], could avoid scaling head's lateral motion. Drift correction techniques should also be tested.

NaviFields' ability to extend the navigable space will also be heavily influenced by the nature of the VE. *NaviFields* will perform well in VEs with a discrete set of relevant areas, spread throughout the space. However, it will degrade to behave like homogeneous scaling if all points of the VE have similar relevance. This can be judged by looking at the gradient of the *navigation field*, as shown in Figure 2D or 4B.

Other alternatives to generate the *navigation field* should also be explored. We described a very simple approach to compute the field, based on cylindrical areas and locations fixed at design time. This allowed us to explore the use of *NaviFields* as a general navigation technique, simplifies understandability and might serve as a general approach, but it is by no means the only way to generate such fields.

As shown at several points throughout the paper, the field can be described as a 2D map showing the scaling factor applied at each point of the VE. Thus, it can be understood as a continuous entity, where the scaling of each point in space can be tailored individually, to adapt to the specific requirements of the VE. The fields could then be automatically inferred, based on the geometry or architectural cues (e.g. doors, alleys, furniture) of the VE.

Alternatively, an open-ended VE (with no a-priori knowledge of which areas are more relevant) could infer this from the user. The VE could initially use homogeneous scaling (i.e. all points in the *navigation field* sharing the same scaling factor). Clustering techniques could then be used, analyzing the points of the VE where the user spends more time, to reduce the scaling factor in those areas (i.e. allow more natural navigation) and increase it in the places where the user spends less time. This could inherently support the learning process in training scenarios, allowing trainees to initially explore the whole environment (e.g. build mental models) and gradually provide adapted support for the areas where they need to spend more time (e.g. workspaces).

The creation/modification of the *navigation field* could also become part of the mechanics of a VR game. In titles such as Gears of War, players need to advance among trenches, which become the guiding element for their navigation (i.e. advance to the next trench and then focus on shooting, taking cover or reloading). With *NaviFields*, identifying such areas could add an element of strategy to such games. Users should specifically identify strategic spots (e.g. by a gate, behind a crate) and create relevant areas there. Our technique would allow precise interaction in those locations and fast transitions between them (e.g. to run from one cover point to the next one).

Finally, the technique has always made use of scaling factors bigger than one. Smaller factors would reduce user motion, and could be used to avoid penetration into objects (e.g. head getting close to a wall). This could also be used to recreate other effects, such as a user stepping on a muddy patch of the floor (or a slippery patch, using a factor bigger than one).

CONCLUSIONS

We presented *NaviFields*, a VR navigation technique that computes the relevance of each point of the VE (*navigation field*) and scales user's motion accordingly. This provides areas of natural navigation (1:1), and faster navigation across non-relevant areas, extending the space users can navigate.

We provided a mathematical characterization of the technique, and implemented it for a testbed environment. We then compared *NaviFields* performance for travelling and maneuvering, comparing it with homogeneous physical displacement and natural navigation.

Our results show that *NaviFields* is a suitable technique to navigate and interact within the virtual environment. *NaviFields* results are comparable to natural navigation in maneuvering tasks, and only slightly worse for travelling tasks. Moreover, when compared to homogeneous scaling of the environment, *NaviFields* is judged better in both travel and maneuvering tasks. Our experimental results also provide insightful information for interaction in VR, highlighting the role of user pose, head position and target size in maneuvering task, and showing that participants can adapt relatively well for scaling factor up to S=2.

We also analyzed the drifting effect observed during the user study, provided a formal model for the effect (reusable for other techniques using differential tracking) and identify strategies to correct it. We finally discussed the scope of application of *NaviFields,* based on its observed properties and the affordances that it enables.

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